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COMPARISON OF RESULTS OF THE HURRICANE DEBBIE (1969) MODIFICATION EXPERIMENTS WITH THOSE FROM ROSENTHAL'S NUMERICAL MODEL SIMULATION EXPERIMENTS

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ABSTRACT

Comparison of the wind-speed profiles, the outer wind envelopes, pressure changes, and possibly the temperature differences that characterized hurricane Debbie before, during, and after the Project STORMFURY seeding experiments of August 18 and 20, 1969, with those calculated in the model simulation experiments of Rosenthal reveals many similarities. Some of the excessive diminution of wind speed noted following the experiment of August 18 may have been due to the vigor and proximity of a synoptic scale trough that appeared to interfere with the upper level diffluent flow from the hurricane.

1. INTRODUCTION

On August 18 and again on Aug. 20, 1969, Project STORMFURY [1] conducted modification experiments on hurricane Debbie. On each occasion, the storm was seeded (with silver iodide) five times within an 8-hr time span—the first times massive repetitive seedings have been attempted. A preliminary report on these experiments by Gentry (1970) presented a few wind-speed profiles across the storm which showed that fairly significant changes in the profiles occurred subsequent to the seeding. The purpose of this paper is to examine these changes at greater length, compare them to model experiments conducted by Rosenthal (1971, appearing as a companion paper) and refer to the large-scale synoptic situation and its possible effect on events. The original hypothesis and accompanying mechanics that justified the STORMFURY experiments have been adequately described elsewhere (Gentry 1969). As a result of the model simulation and field experiments, a new concept is beginning to emerge. This will be mentioned briefly in a later section.

2. WIND-SPEED PROFILES

For focusing attention on what we consider the critical and typical alterations to be brought about by the seeding, we cite Rosenthal's (1971, sec. 5) companion paper. The changes in the surface wind-speed profile that characterize the model experiments (which simulate the proposed seeding effects) are:

1. Displacement of the ring of maximum winds outward to greater radii.
2. Reduction in the speed of the maximum winds—a reduction is suggested of the order of 10–15 percent.
3. An increase in wind speeds at greater radii (i.e., outside the maximum) in the envelope surrounding the central storm area. The increases are again of the order of 10 to 15 percent between the maximum wind and the 90-km radius.

[1] Project STORMFURY is a joint undertaking of NOAA (Department of Commerce) and the U.S. Navy with the cooperative support of the U.S. Air Force.

The only extensive wind-profile data gathered in the experiments were from the 12,000-ft level. It should be noted that, in a typical mature hurricane of moderate intensity (maximum winds around 90–100 mi/hr), we are reasonably confident that any significant changes in speed near the core of the storm at this level will also be reflected at the surface (Hawkins 1962). In any event, changes noted at 12,000 ft should be compared with the 700-mb changes (presented in fig. 8 by Rosenthal 1971). Our extensive experience with hurricane wind-speed profiles suggests that the wind maximum in Rosenthal's model occurs near 25 km and is of the order of 40 m/s (80 mi/hr). Unfortunately, this falls between grid points; and the drawings, taken literally, suggest that the wind maximum increases slightly after the seeding. It seems likely that little or no change in the maximum speed should be anticipated at 700 mb, but a significant shift outward to larger radii can be expected with some small increase in speed of the outer envelope.

It is a well-known fact that wind speeds on the right-hand side of the storm (looking in the direction toward which the storm is heading) are stronger than the winds on the left. This phenomenon can be associated with the greater radius of trajectory curvature associated with parcels moving cyclonically on the right of the storm than on the left (La Seur and Hawkins 1963). Consequently, wind-speed profiles can be meaningfully compared only when cognizance is taken of the azimuth (relative to the storm) characterizing a particular radial pass or profile. These differences are readily apparent in the accompanying profiles in which the storm is moving toward about 330° on the 18th and turning from 330° to 360° on the 20th.

INNER CORE WIND-SPEED PROFILES AND CHANGES ON AUGUST 18 AND 19

Seedings on the 18th occurred at 1423, 1634, 1813, 2002, and 2153 GMT. The seedings extended generally over radii of 20 to 40 n.mi. at azimuths between 345° and

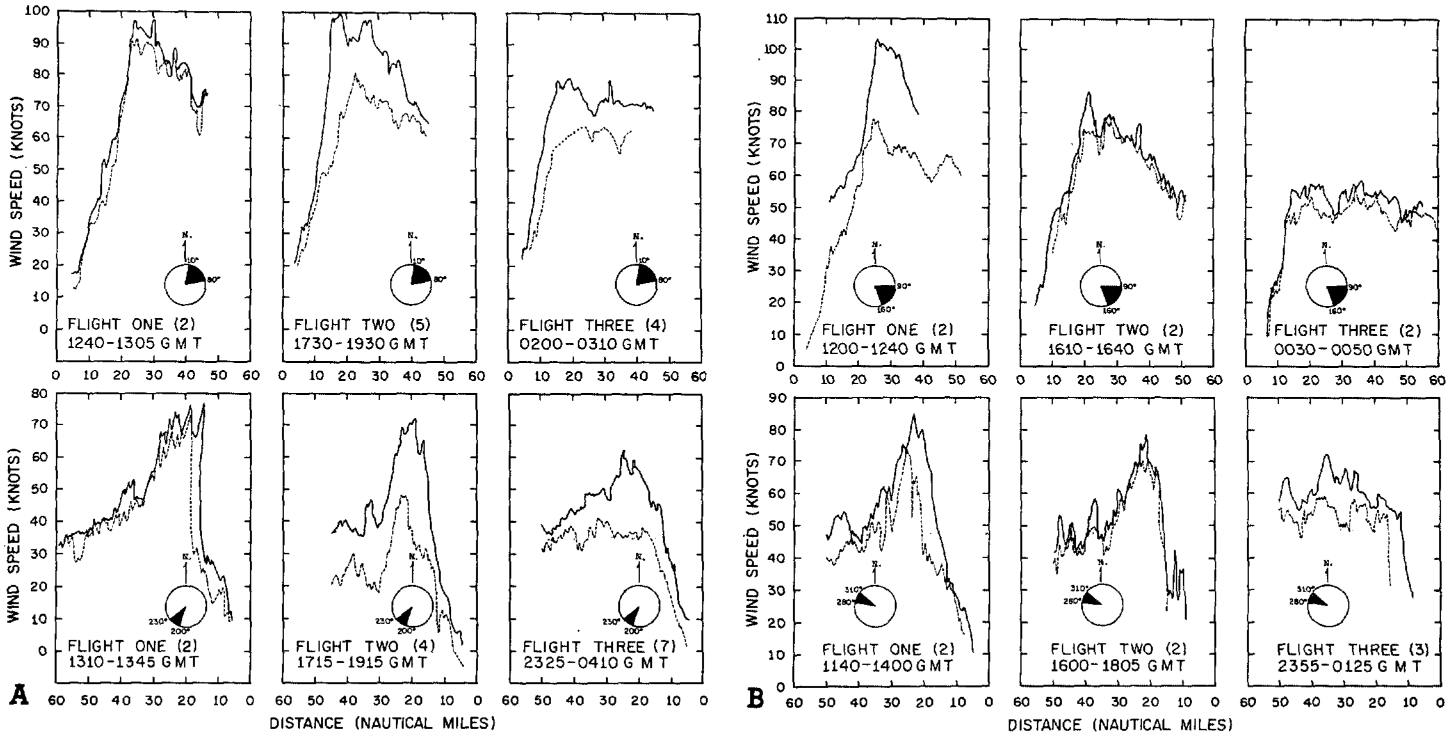

FIGURE 1.—Wind-speed envelopes (at 12,000 ft) on August 18 and 19 showing the maximum and minimum wind speed at the indicated radial distance for the available number of radial passes (noted in parentheses). The profiles are segregated according to azimuth angle relative to the storm center. The left panels depict pre-seeding conditions, the central panels are roughly from mid-seeding conditions, and the right panels show post-seeding envelopes.

030° (clockwise). The burning pyrotechnic devices left trails of silver iodide "smoke" (from 33,000 to about 18,000 ft) as they fell. Doppler wind measurements taken in past hurricanes (Hawkins 1962, La Seur and Hawkins 1963, Hawkins and Rubsam 1968) indicate the existence of cyclonic winds of diminished strength above and immediately outside the ring of maximum winds. The winds in the seeded layer will carry an expanding curtain of silver iodide around the eye of the storm. Some of the nuclei will be carried aloft, some will fall out in rain, some will become inactive, but many should continue to exist for the hour or so it takes for the inner portions of the curtain to complete the circumnavigation. In Rosenthal's two-dimensional model, there is no possibility of exact duplication of this gradually spreading curtain effect. The model allows heating only at one azimuth, which is in effect *all* azimuths and, at "all azimuths," simultaneously. This is not thought to be a fatal weakness in the model simulation, although it is obviously not a strong point.

Figures 1 and 2 present envelopes of the wind speeds encountered at the indicated radii on the number of passes (shown in parentheses) between the azimuths indicated by the sectors in black during the times listed. Flights one, two, and three were made by two of NOAA's Research Flight Facility DC–6's. These planes are heavily instrumented and well calibrated. Wind speeds are recorded every second, which is probably faster than the response time of the sensor and recording system. These "one second" winds have been arithmetically smoothed or averaged over 11 s. The profiles are produced on a Calcomp[2] plotter, which plots a value for every fifth second. In these figures, the upper and lower traces indicate the maximum and minimum wind speed at each radius.

The upper row of panels in figure 1A shows envelopes of wind speeds in the right front quadrant (to the right of the direction of motion) before, during, and after the seedings. The maximum wind speeds obviously decreased from 95 to 100 kt before to around 70 kt after the seedings (although not all of the profiles were complete—some data were missing). The maximum after the seedings is very poorly defined, so poorly that it is difficult to determine whether or not the maximum has been moved out. On the other side of the storm (panels shown below with azimuth 200°–230°), maximum winds were weaker initially (around 75 kt) and weakened to a state where six of seven passes after the seedings had maxima of 47–54 kt. The one exception was the very first pass with a maximum of 63 kt. Furthermore, there was a fairly definite trend for the radius of maximum winds to expand, averaging about 15–20 n.mi. before to greater than 20 n.mi. after the seeding.

The passes approximately at right angles to those of figure 1A were alined roughly parallel to the direction of motion of the storm; these data show very similar sequences (fig. 1B). The two early passes between 90° and 160° evidenced wide variability in the wind maximum with 103 kt at 90° and 79 kt about 30 min later at 130°. The final passes (upper right panel) at 160° had maxima of just about 60 kt. Once again, the final profile is so flat

[2] Mention of a commercial product does not constitute an endorsement.

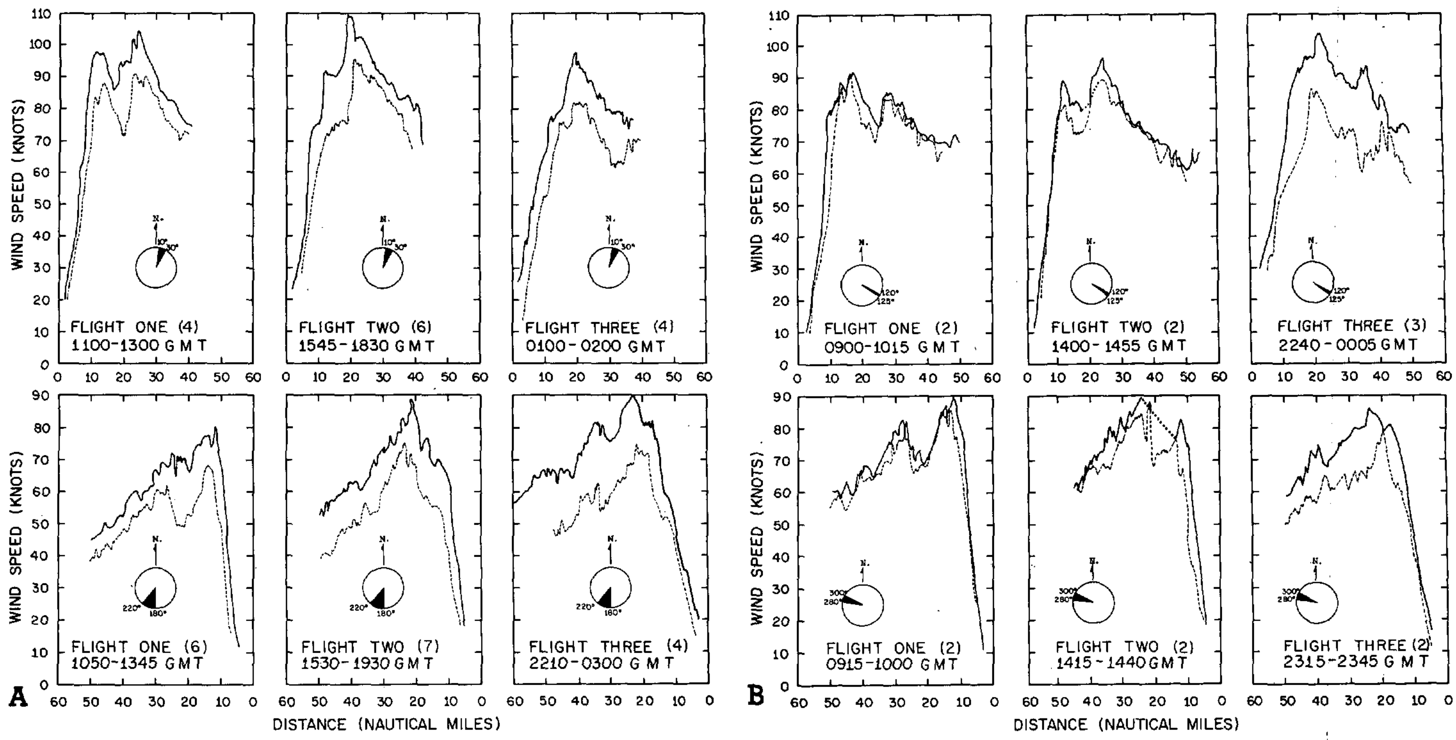

FIGURE 2.—Wind-speed envelopes (at 12,000 ft) for August 20 and 21; see the caption of figure 1.

that it is difficult to maintain that any major maximum has been shifted outward. Rather, the well-defined inner maximum has been all but obliterated.

The profiles from the forward quadrant (280°–310°) behaved quite similarly. The pre-seeding maxima were 75 to 85 kt. After the seeding, they were 73, 66, and 67 kt. Perhaps even more important was the almost complete elimination of the inner maxima around the 25-n.mi. radius leaving a very flattened wind-speed profile.

SUMMARY OF THE WIND-SPEED PROFILE CHANGES IN THE CENTRAL CORE (0- TO 50-NAUTICAL MILE RADII) OF HURRICANE DEBBIE ON AUGUST 18 AND 19

There is little doubt that significant changes occurred in the inner wind structure of hurricane Debbie subsequent to the seedings of August 18. Items of apparent portent are:

1. The wind-speed maxima decreased by amounts that exceeded the most optimistic estimates of STORMFURY advocates and exceeded any drops suggested by the model experiment.
2. The changes seemed to involve a flattening of the innermost peak of maximum winds and a flattening of the inner area profile, so that the residual high winds were spread over a pleateau with poorly defined maxima or maximum.
3. The new maxima were generally at greater radii than the initial maxima.
4. Subjectively, the profiles following the seedings do not look "normal." The inner peaks in hurricane profiles are usually well defined, although other plateaus of fairly high wind speeds are not uncommon in mature storms.

INNER CORE WIND-SPEED PROFILES AND CHANGES ON AUGUST 20 AND 21

During the major part of August 19, the hurricane apparently recovered from the changes noted from August 18 to the early hours of August 19. When the research planes returned around 0900 GMT on August 20, the wind speeds were as strong or stronger than those on August 18.

A feature of special note was the "double eye wall" structure and the double wind maximum. Double wind maxima have been documented in such circumstances before, but the situation has a reputation of being a relatively unstable one. By this is meant that the inner (or possibly outer) wall cloud may strengthen, weaken, and disappear over a period of hours and may reform again in a period of 1 or 2 hr. This was obviously not the ideal storm on which to experiment, but it did pose a challenging question. Which wind maximum should be attacked? If the outside of the inner maximum were seeded, then the seeding would be on the inside of the outer maximum. The model experiments suggested this might call for little change in the outer maximum.

Seeding drops were made at about 1157, 1402, 1614, 1758, and 1955 GMT on August 20 at azimuths from about 000° through 040° (clockwise). The sequence of profiles at various azimuths are presented for August 20 in figures 2A and 2B, as was done previously for August 18.

The upper row of panels (fig. 2A) shows that the double wind maximum structure remained very stable through the first seeding. Each of the four passes showed double maxima, with the outer maxima (range 95–106 kt) usually slightly stronger than the inner maxima (range 89–98 kt). Since these profiles were gathered over a 2-hr period, we must conclude that this feature was relatively stable on the short time scale.

Flight two by the second DC-6 shows the inner maximum (middle panel) diminishing with possibly some minor strengthening of the outer maximum (no pass recorded a maximum of less than 100 kt). This period extended through all but the last seeding.

The final passes in the "strong" quadrant of the storm are shown in the upper right panel. They show continued suppression on the inner peak, although the possibility of an incipient "bud" is still apparent. Moreover, the maxima have diminished, showing peak speeds of 97, 88, 92, and 84 kt in successive (chronological) passes.

On the other side of the storm (sector 180°–220°), the winds are weaker to begin with (lower panels, fig. 2A). The double maximum structure was not as well-defined in the envelopes initially, but was noted on every pass. In addition, the inner maximum was consistently as strong or stronger than the outer maximum. Panel two in this row shows the suppression of the inner maximum and some strengthening of the outer maximum. The final passes (last panel) in this sector evidenced some extreme fluctuations in speed from a maximum of 78 kt (on a pass at 0047 GMT on the 21st) to a maximum of slightly over 90 kt. These post-seeding values do not represent much change in the maximum wind speeds in this sector from those observed prior to seeding.

The opposite sectors (fig. 2B) contain a lesser number of passes usually fairly close together in time. The double maximum structure is evident in both the 120°–125° and the 280°–300° sectors before the start of the seeding and, in the second panels, is shown to continue through the second seeding. The final flights in these sectors terminate rather early (0005 GMT on the 21st) but show the erosion of the inner maximum and, in the 280°–300° sector, show a slight weakening of the outer maximum over the original peak winds observed in the inner maximum.

SUMMARY OF INNER CORE (0- TO 50-NAUTICAL MILE RADII) WIND-SPEED CHANGES ON AUGUST 20 AND 21

1. On the time scale of hours, the double maximum structure in the wind field appeared relatively stable.
2. After the seeding (outside the inner maximum), erosion of the inner maximum occurred.
3. There is some suggestion in the figures that the two maxima may be looked on as merging.
4. The outer maximum was outside most of the seedings and did not weaken significantly except in the right quadrant (where the strongest winds were originally found).
5. These changes are not at variance with those called for in the hypothesis or suggested by the model experiments.

PERIPHERAL CHANGES IN THE WIND-SPEED PROFILES (50- TO 200-NAUTICAL MILE RADII)

From the areal spread of the wind-speed envelopes (figs. 1 and 2), one obtains some appreciation of the variability of the wind from one pass to the next. Also, it becomes apparent that citing one figure (i.e., a wind-speed maximum) to characterize the strength and structure of a storm may be a useful synopsis, but can be misleading. For similar reasons, relying on individual passes or profiles is not a method that always guarantees representative profiles. Nevertheless, it is felt that the peripheral

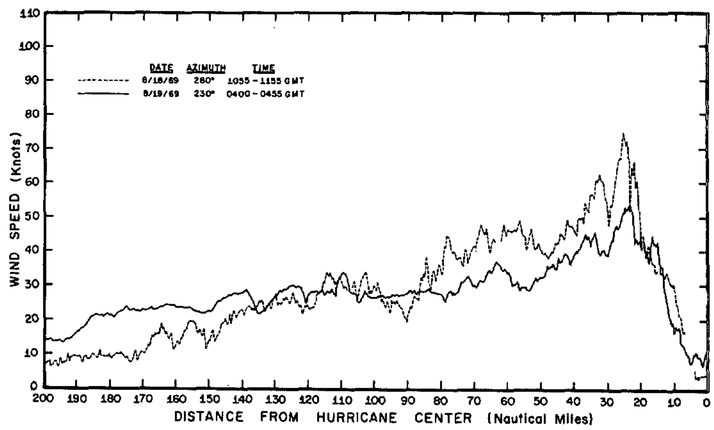

FIGURE 3.—Wind-speed profiles (12,000 ft) from the original approach to hurricane Debbie on August 18 (before the seeding with silver iodide) and the final exit long after the seeding on August 19.

winds should be presented, even though at these large radii only one original entry pass and one final departure pass are available for each experiment.

The reasons for this emphasis lies in the implications of Rosenthal's model simulation runs. His conclusion that "the artificial heating was not only effective in itself" but further that "its presence induced an increase in natural rainfall" is an observation of potentially great significance. It is, in fact, giving rise to a new modification hypothesis. If this aspect of the model runs should prove to be representative of what happens in a seeded storm, it would imply that energies above and beyond those released by the actual seeding would be called into play. This is the first intimation of the chain type of reaction that physical scientists have hoped to trigger by artificial means. Many countries would benefit more from the rains that accompany a hurricane if the rain could be disseminated over a wider area. There is also the less pleasant implication that more energy will be released, that the outer envelope of winds (out to 100 km and more) will acquire slightly higher velocities—hopefully, the increase will be restricted to the regions where wind speeds are not dangerously high before seeding. For these reasons, it was thought advisable to look at the earliest and latest extended wind profiles for each of the experiments, despite the danger that they may not be representative.

The approach and exit profiles for August 18–19 (fig. 3) should be roughly comparable. The approach, from about 1100 to 1200 GMT on the 18th was approximately along the 270° storm azimuth. This may be compared with the exit profile that was gathered along the 230° azimuth between 0400 and 0500 GMT on the 19th. The inner 100 n.mi. show nothing but decrease in wind speeds that occurred over this time interval. This widespread diminution was not suggested by the model runs and must be accepted as a significant lessening of the storm's kinetic energy over the inner region. Beyond a 110-n.mi. radius (at least out to 200 n.mi.) wind-speed values of the final profile exceed those of the pre-seeding profile. These do not compare well

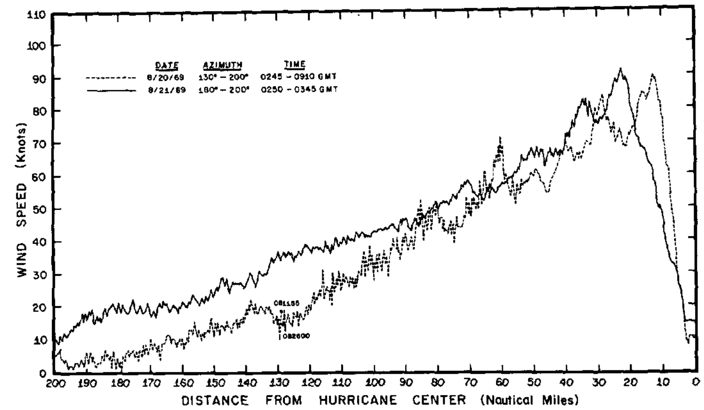

FIGURE 4.—Wind-speed profiles (12,000 ft) from the original approach to hurricane Debbie on August 20 and the final exit on August 21. (On the approach, the aircraft did not reach a 12,000-ft altitude until reaching the 175-n.mi. radius, but was above 8,000 ft when passing 200 n.mi.)

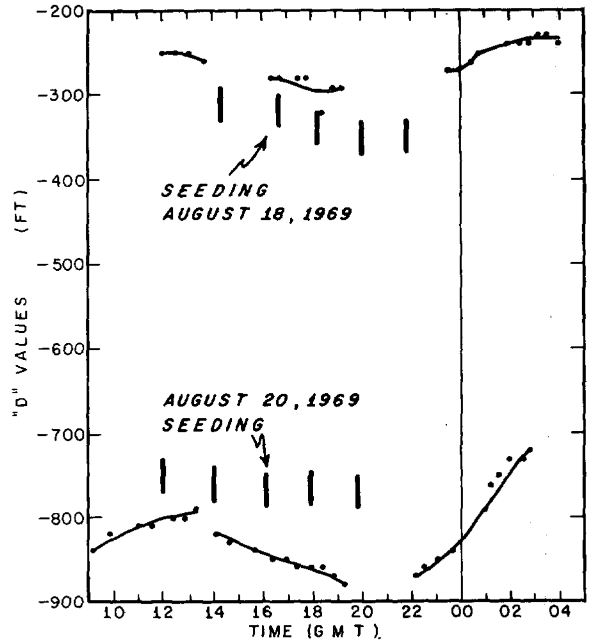

FIGURE 5.—D values at 12,000 ft from the eye of hurricane Debbie. These are successive measures of the central "pressure" of the hurricane before, during, and after the two seeding experiments on August 18 and 20. D values are observed during successive passes by the DC–6 aircraft and have been subjectively adjusted to compensate for distance from the actual traverse to the center of the eye. Dots show actual values; the middle curves have been "adjusted" to fit the level of the first and last flights.

with the model experiments which suggest that the maximum increase might be around 60 km (~ 32 n.mi.) and that only minor increases would be noted at radii greater than 100 km (~ 54 n.mi.). Profiles out to 200 n.mi. have been offered just to see what changes, if any, occurred at these radii.

Profiles for the experiment of the 20th (fig. 4) are possibly a little more in line with the model results. The approach (from about 0800 to 0900 GMT on the 20th) was not along a radial to the storm, and azimuths varied from 130° to 200° or more. The exit profile (from about 0300 to 0400 GMT on the 21st) was oriented near the 190° azimuth. One's first impression is that the inner features (the double maxima) have been displaced outward with not much change in intensity. We have, however, already noted that the intermediate stage (center lower panel, fig. 2A) suggests that there was a stage where the inner peak (10–12 n.mi.) was eroded away and only one fairly well-marked peak (20–22 n.mi.) remained. So, the emergence of a new peak near 35 n.mi. is a more recent development. Aside from these points, the final exit speeds exceed the approach speeds almost everywhere at radii greater than 20 n.mi. Because no simulated experiment has been run on a model with a double wind maximum, comparisons are apt to be dangerous. Nevertheless, there is no flagrant contradiction in what the model indicated or allowed us to infer in the observed wind-speed profiles other than the excessive speed decreases of August 18 and 19.

PRELIMINARY CONCLUSIONS

Changes evidenced in the character of the wind-speed profiles subsequent to the seedings on August 18 and 20 were of such a nature as to be consistent with the STORMFURY hypothesis and with the model experiments. However, the marked diminutions of speed on August 18 seem to be beyond reasonable expectations of magnitude changes to be effected at this level by seeding, and the inner maximum that eroded so well on August 20 is not usually considered a notably stable feature.

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3. CENTRAL PRESSURES

The central pressure of the hurricane is not shown as changing greatly in the course of the simulation experiment (see Rosenthal, fig. 9). The maximum suggested change in surface pressure is of the order of 3 mb, an initial fall during the seeding followed by a rise after the cessation of seeding. A change of this magnitude is about the smallest that can be detected using aircraft dropsondes—assuming one can locate the center of minimum pressure and drop a sonde into it.

In view of the accuracy required, it was decided to use the 700-mb D values acquired by the DC–6s on their successive penetrations of the eye. Since the planes did not always pass through the exact center of the eye, subjective adjustments, mainly of a minor nature, were made to compensate for these differences. D values at 12,000 ft for August 18 and 20 (fig. 5) suggest the following:

1. Hurricane Debbie was considerably deeper on the 20th than on the 18th (i.e., −800-ft vs. −250-ft D values or approx. 17mb).
2. The sequence of short-period time changes were similar to those in the model experiment (i.e., there was some minor deepening during the seeding that was of the order of 50 to 100 ft in D value change, approx. 1 to 2 mb).
3. The center filled after the cessation of seeding, with D values rising to levels higher than before the seeding began. This, too, is in agreement with the model experiments.
4. The rise on August 20 was almost twice that on August 18, which at first glance appears inconsistent with the changes in the wind-speed profiles. However, this apparent inconsistency may be explained by the D values in table 1 which have been selected as "representative" from the typically noisy D value traces and which should be reliable to ± 10 or 15 ft.

TABLE 1.—*D values (in feet) at 12,000 ft for selected radial distances from the eye of hurricane Debbie (1969)*

Flight	Date	Type	GMT	Radial distance (n.mi.)				
				200	150	100	75	50
1	8/18	Approach	1120	615	605	540	480	350
3	8/18-19	Exit	0430	585	565	490	450	350
1	8/20	Approach	0810	not at alt.	550	505	465	320
3	8/20-21	Exit	0330	695	675	565	465	290

Within the limitations of the data accuracy, it appears that the weakening of August 18–19 was associated more with falling D values (falling pressures) at radii out to and beyond 200 n.mi., rather than to any dramatic rise in the central pressure itself. Gradients of D values seem to have increased slightly beyond the 100-n.mi. radius and are in agreement with the increased peripheral wind speeds. On August 20–21, D values are approximately the same at 75 n.mi. before and after the seeding. The central pressure rose a little, possibly accounting for the decrease in winds between 10 and 20 n.mi. On the other hand, D values rose at the 100-, 150-, and presumably 200-n.mi. radii with increasing gradients and wind speeds.

The short-term central pressure changes were of the nature and scale of those suggested by the model simulation runs. An outer increase in peripheral wind speeds was noted following each seeding experiment. It is impossible to say just how representative these increases were since data to these radii were available at essentially only one azimuth. But within the confines and limitations of the data, agreement with the simulation runs was good.

4. TEMPERATURES

The simulation experiments suggest that noticeable temperature changes should accompany the seeding. These are mainly confined to the upper atmosphere at 500 mb and above (Rosenthal, fig. 10). For instance, the temperature difference at 300 mb between 45 and 15 km is supposed to diminish from 3° to 1.5°C, while the difference at these radii at 500 mb decreases from 1.5° to about 0.0°C. At 700 mb, the changes noticed in the simulation were quite small and inconsequential.

Unfortunately, temperature data from Debbie for before and after seeding from the upper atmosphere were not obtained due to lack of aircraft. An Air Force WB–47 obtained wind and temperature measurements at 39,000 ft about midway through the seeding on August 18. These data showed temperatures averaging −47° to −48°C at a radius of 75 n.mi. and −43°C in the eye. Another Air Force aircraft, a WC–130 at 31,000 ft, recorded temperatures of −28° to −29°C, 80 to 90 n.mi. from the storm and −23°C in the eye. This level is quite close to 300 mb in the mean tropical atmosphere and suggests a difference of about 3.5°C between 45 and 15 km (24 and 8 n.mi.), in good agreement with the pre-seeding period of the simulation experiment. There is no post-seeding run at this level in Debbie, so any weakening of the gradient remains undocumented.

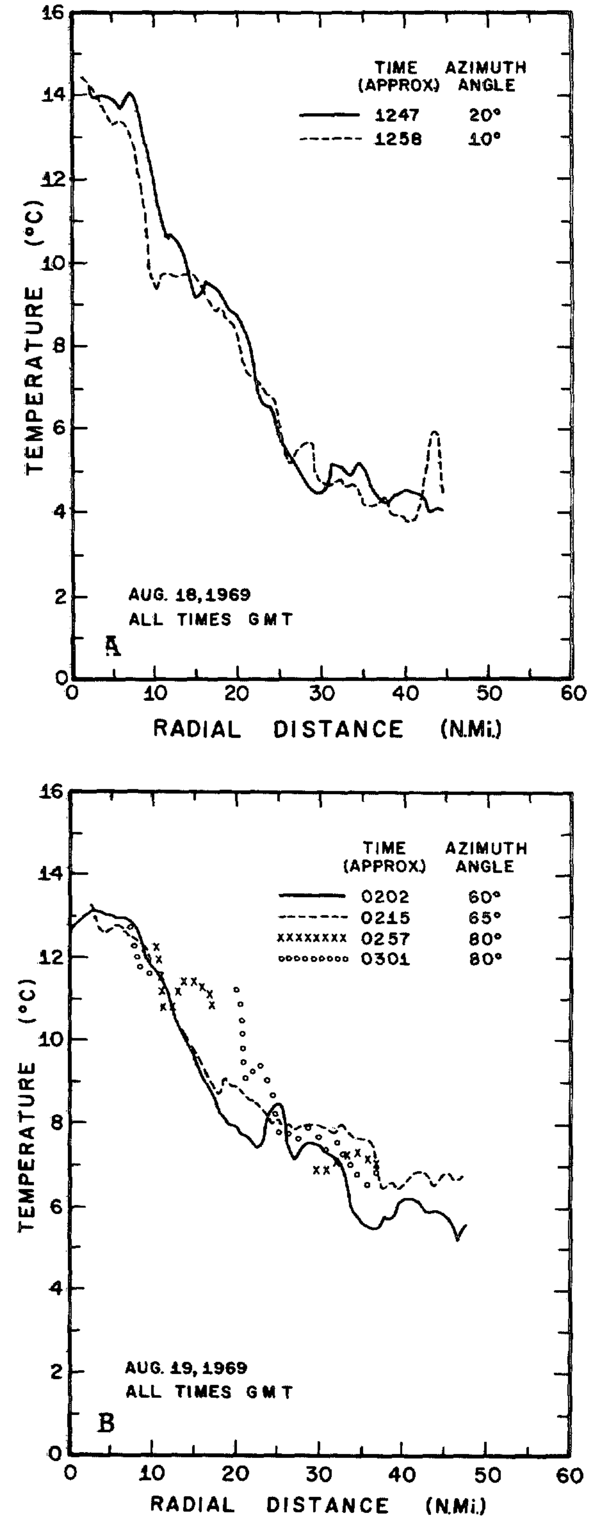

FIGURE 6.—Typical temperature profiles at 12,000 ft (A) before and (B) after the seedings of August 18. Almost all profiles suggested a decrease in eye temperatures and an increase in peripheral temperatures around a radius of 30 to 40 n.mi.

There are data at the 12,000-ft (DC–6) level, and we will mention these briefly, despite the fact that it may be highly dubious that this temperature field should be closely related to that at 300 mb, particularly when the upper field is undergoing artificial manipulation.

Typical temperature profiles at 12,000 ft before and after the seeding (figs. 6A and 6B) show that the inner 40-mi gradient decreases considerably from 10°C/40 n.mi. to around 7°C/40 n.mi. Other quadrants evidenced much the same change with temperatures increasing slightly (around 1°C) at the 40-n.mi. radius and decreasing a larger amount (around 2°C) in the eye. The 12,000-ft gradient would be expected to be greater than that at 31,000 ft (Hawkins and Rubsam 1968) in the outflow layer. It is conceivable that the weaker wind maximum following the seeding is accompanied by weaker subsidence in the eye of the storm and a fall in the eye temperatures; but the eye temperature changes cannot be very great through a thick layer because the pressure changes in the eye are not large.

On August 20, the WB–47 did not penetrate to the eye of the storm, so no temperature differences are available at 39,000 ft. Temperatures at radii of 75–85 n.mi. were consistently about −47°C and showed little change from those of the 18th at comparable radii. The WC–130 (on the 20th) found eye temperatures ranging around −20° to −21°C, a few degrees higher than on August 18. The temperature difference (45 to 15 km) appeared to be about the same as on the 18th, although temperatures around 90 n.mi. out averaged −27° to −28°C. At 12,000 ft, the eye temperatures reached 16°C on every penetration before the seeding. Temperatures 40 n.mi. out were consistently 5° to 6°C. After the seedings, eye temperatures were around 14°C, and temperatures at a radius of 40 n.mi. were about 6° to 7°C. These changes are very similar to those that occurred on the 18th, despite the fact that changes in the storm differed considerably from one experiment to the next. It should be pointed out that the increased diameter of the eye (on the 20th) as the ring of maximum winds expanded may well have spread the limited subsidence that was occurring over a much larger area, so that the temperatures in the eye were lower than before the expansion. Also, it must be borne in mind that the simulation experiments suggested only very minor temperature changes at this level.

5. SUMMARY OF RESULTS

The data reviewed here suggest to this author that the silver iodide seedings did have an effect on hurricane Debbie, which in a number of ways paralleled the reaction of Rosenthal's model to the simulated seedings. These items may be listed as follows:

1. The erosion of the innermost wind maximum beyond which the seedings took place and its displacement outward were most striking on the 20th. On the 18th, the wind maximum was mightily affected; but the resulting profiles were on occasion so flattened that a new radius of maximum winds was difficult to specify.

2. A general diminution in the wind field took place on August 18 and 19 when seedings were outside the single wind maximum. Actually, the simulation experiments do not suggest any major reduction in speed at 700 mb. It is felt that, in all probability, some significant portion of this reduction may have been due to synoptic events discussed shortly.

3. In the experiment of August 20, the maintenance of the outer wind maximum (seedings were mostly inside at smaller radii) was much as called for in the simulations—although no simulations were run with double maxima. A much more modest diminution of wind speeds (than on the 18th) was noted in some quadrants.

4. An increase in speed of the peripheral envelope of winds was noted in each experiment as suggested by the simulations. These had to be gaged by single passes, and the observation must be accepted with reservations.

5. Central pressures, as indicated by D values at 12,000-ft altitude, closely parallel those of the simulation experiment in relatively fine detail.

6. Temperature data were inadequate to confirm or deny similarity to the simulation results. If one is willing to accept 12,000-ft temperature gradients and their changes as representative of 300-mb gradients and their changes, there was a weakening of the thermal gradient between the eye and the area beyond the ring of maximum winds. However, the simulation experiments did not indicate significant temperature changes at 700 mb. Consequently, the contribution of the 12,000-ft temperatures may be considered dubious.

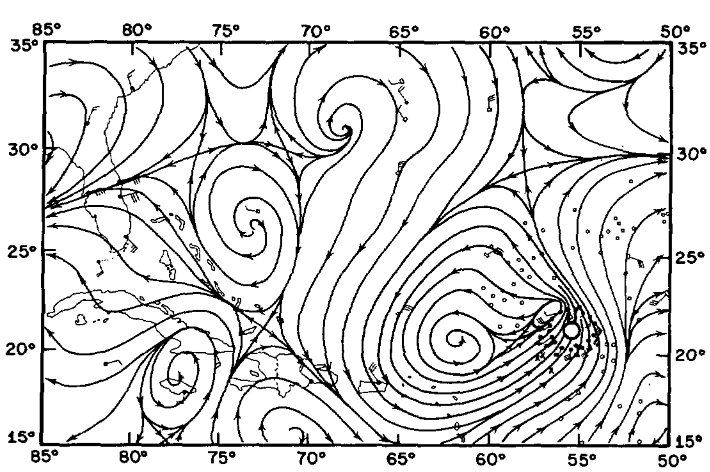

Figure 7.—Streamlines at 200 mb at 0000 GMT on Aug. 19, 1969. Hurricane Debbie is located near 22°N, 55°W.

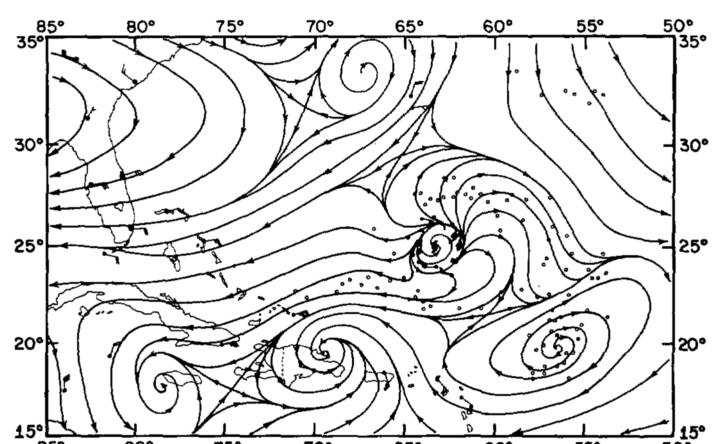

Figure 8.—Streamlines at 200 mb at 1200 GMT on Aug. 20, 1969. This has come to be considered as a "normal" upper level circulation for a mature vigorous hurricane surrounded by a diffluent upper level protective ridge. See caption of figure 7.

6. SYNOPTIC INFLUENCES

In view of the startling diminution in wind speeds following the seedings of August 18, we felt compelled to examine the synoptic aspects of the situation to see if any pertinent statements could or should be made. For this purpose, the synoptic maps surrounding the experiment were replotted, taking advantage of late data, satellite winds, and special winds compiled from data logged during the experiments themselves. With the aid of these analyses at the 200-mb level, a number of observations are permissible:

1. Hurricane Debbie moved west-northwestward and northwestward in an area of little or no upper air observations prior to the 18th.

2. As Debbie turned northwestward while approaching the Lesser Antilles, it began to enter the domain of the mean upper level trough usually found in this area.

3. The trough was present and active (winds of 30 to 40 kt) on this occasion. It was, in part at least, being influenced by the ridge over the southeastern United States that accompanied hurricane Camille. We have seen many hurricanes enter the mean trough domain. In the usual case, the daily trough moves westward with the upper level diffluent ridge accompanying the hurricane dominating the area of the eastern trough. In this instance, the hurricane appeared to be overtaking the trough and to have entered its eastern periphery.

4. There is evidence from the WB-47 flights at 39,000 ft (fig. 7) that the cyclonic flow from the trough penetrated almost to the eye of the storm at this level. This is a most unusual data set and might be discarded as suspect, but they are reinforced by similar southwesterly winds almost into the core of the storm reported by the WC-130 at 31,000 ft. The winds near the storm are plotted on figure 7 as frequently as space permits (more are available). Conventional radiosonde data are indicated by large black circles, and commercial aircraft reports (usually off time and at somewhat lower levels) are indicated by open squares. Open circles indicate "satellite winds" for which streamlines have been drawn. These winds suggest an unusual intrusion of upper atmospheric air into the core of the storm. Asymmetry in the cirrus cloud shield (shifted to the north and east of the eye) during part of the 18th tends to support this phenomenon.

5. Winds derived from satellite photographs near the storm and to the south on August 18 do not support this circulation (crosses on fig. 7), but they probably refer to too high a level since the cirrus overcast was above the WB-47 when it was south of the storm. The satellite winds from cirrus not associated with the storm but still further south seem to support the cyclonic intrusion and are likely to be at a more pertinent level.

6. It is undoubtedly safe to say that not all meteorologists would agree on just what affect such an intrusion (or high-level ventilation) would have. We believe that the interference with the upper level divergence pattern or mechanism was associated with at least some of the weakening of the winds noted from August 18 to early August 19. This weakening was not forecast in the official advisories (but then the winds showing the intrusion were not available when the forecasts were made); nor is it self-evident what the forecast should have been even if the winds were accepted—and they still are difficult to accept. In an attempt to resolve this problem, we have asked the National Aeronautics and Space Administration (NASA) to prepare enhanced photographs from which we can prepare film loops to derive more detailed winds of higher accuracy. But these will probably not be applicable to the inner area and level where the unusual winds were recorded. It must be pointed out that there is also the distinct possibility that the unusual winds are a result of the weakening—perhaps associated with the seeding—and not an independent contributing cause of the weakening.

7. A circulation pattern that we have come to believe is more usually associated with a mature steady-state hurricane is shown in figure 8. Most of the winds used to define the pattern are satellite winds and may (quite close to the storm) be representative of levels slightly above the 200-mb level. In any event, the protective environment formed by the ridge is quite evident, and hurricane Debbie on August 20 was a mature vigorous storm.

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